Characterizing Submesoscale Ocean Currents Using a Doppler Scatterometer

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Why Winds and Surface Currents? Why Submesoscale?

- Both are essential climate variables that have a tight two-way coupling
  - Stress and stress derivatives drive both horizontal and vertical circulation
  - Currents provide a moving reference frame for stress and also modulate winds through heat transport/SST
- The 2017 NRC Decadal Review, ***Thriving on Our Changing Planet A Decadal Strategy for Earth Observation from Space***, has identified "***Coincident high-accuracy currents and vector winds to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift***" as a targeted observable for a potential Earth System Explorer mission (competed).
  - Doppler scatterometry identified as a measurement technique
  - DopplerScatt (NASA IIP) is a proof of concept instrument to validate measurement physics, algorithms, technology readiness.
- ***Submesoscale ocean circulation*** (spatial scales 200m – 25 km, $|\zeta/f| > 1$) is suspected suspected to be responsible for significant vertical air-sea fluxes that can be larger than the global radiation imbalance associated with the greenhouse effect (Su et al., 2018) and cannot be measured yet from space.

DopplerScatt Overview

DopplerScatt Programmtic Overview

Scanning Doppler radar developed under NASA's IIP program
Becoming operational under NASA AITT program by 2019

Data Products:

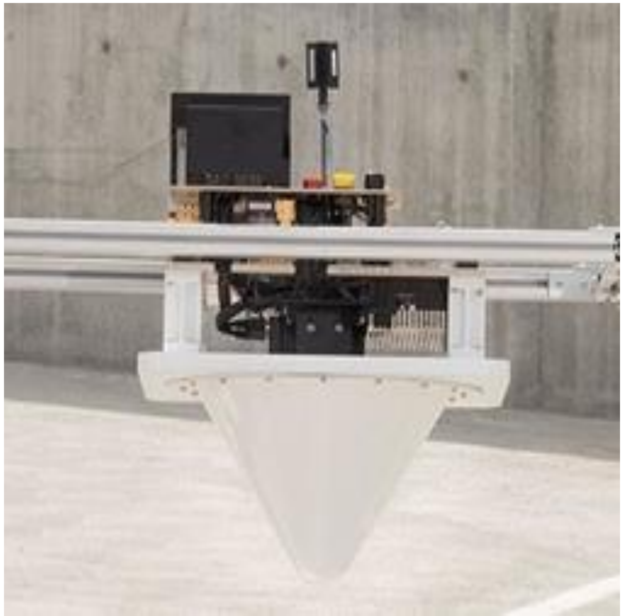
1.Vector ocean surface currents
2.Vector ocean surface winds
3.Radar brightness maps (sensitive to surfactants such as oil films)
4. Surface wave 2D spectra (experimental)
Data products are still being refined under AITT. Will be posted in NASA PODAAC when finished.

Mapping capabilities:

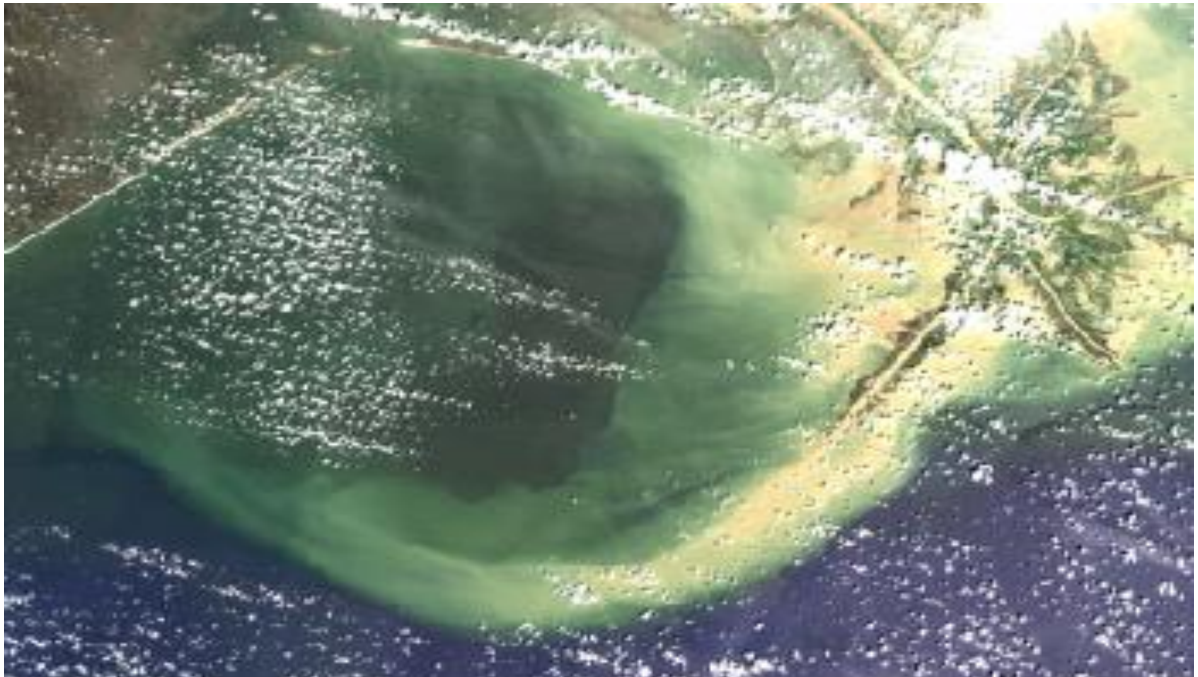
- 25 km swath
- maps 200km x 100km area in about 4 hrs
- 200m data product posting
- Mapping within ~600 m of coast
- ~5-10 cm/s radial velocity precision.
- ~ 1 m/s wind speed, <20^{o} wind direction.

Campaigns flown/planned:

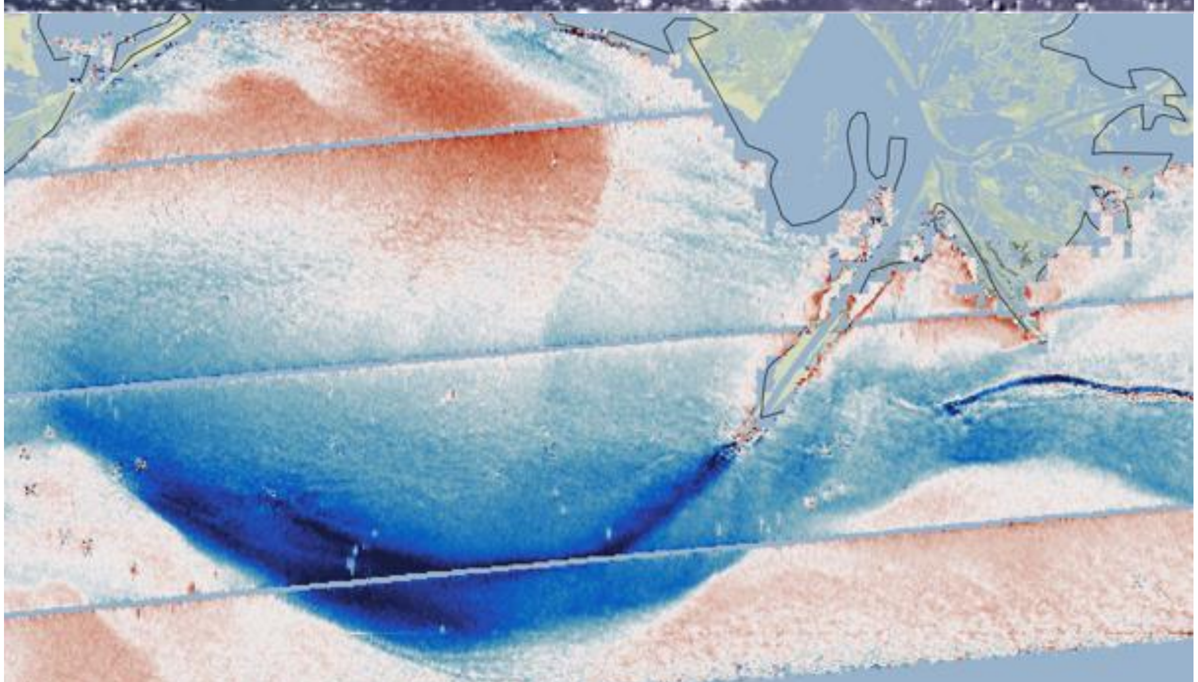
- Oregon coast (2016)
- SPLASH (Submesoscale Processes and Lagrangian Analysis on the Shelf) in Mississippi River Plume
- (CARTHE) & Taylor Oil Platform Plume (NOAA), April 18-28, 2017.
- KISS-CANON in Monterey Bay May 1-4, 2017.
- Gulf of Mexico Eddy/Chevron (March, 2018)
- California current (August, 2018)



DopplerScatt instrument. It has been deployed on a DOE King Air and will transition to an operational instrument in the NASA King Air B200.



Sentinel 3 2017-04-18
Courtesy of Copernicus Sentinel, processed by ESA



DopplerScatt surface current U component.

Circulation pattern, including submesoscale front, matches Sentinel 3 color pattern very closely.

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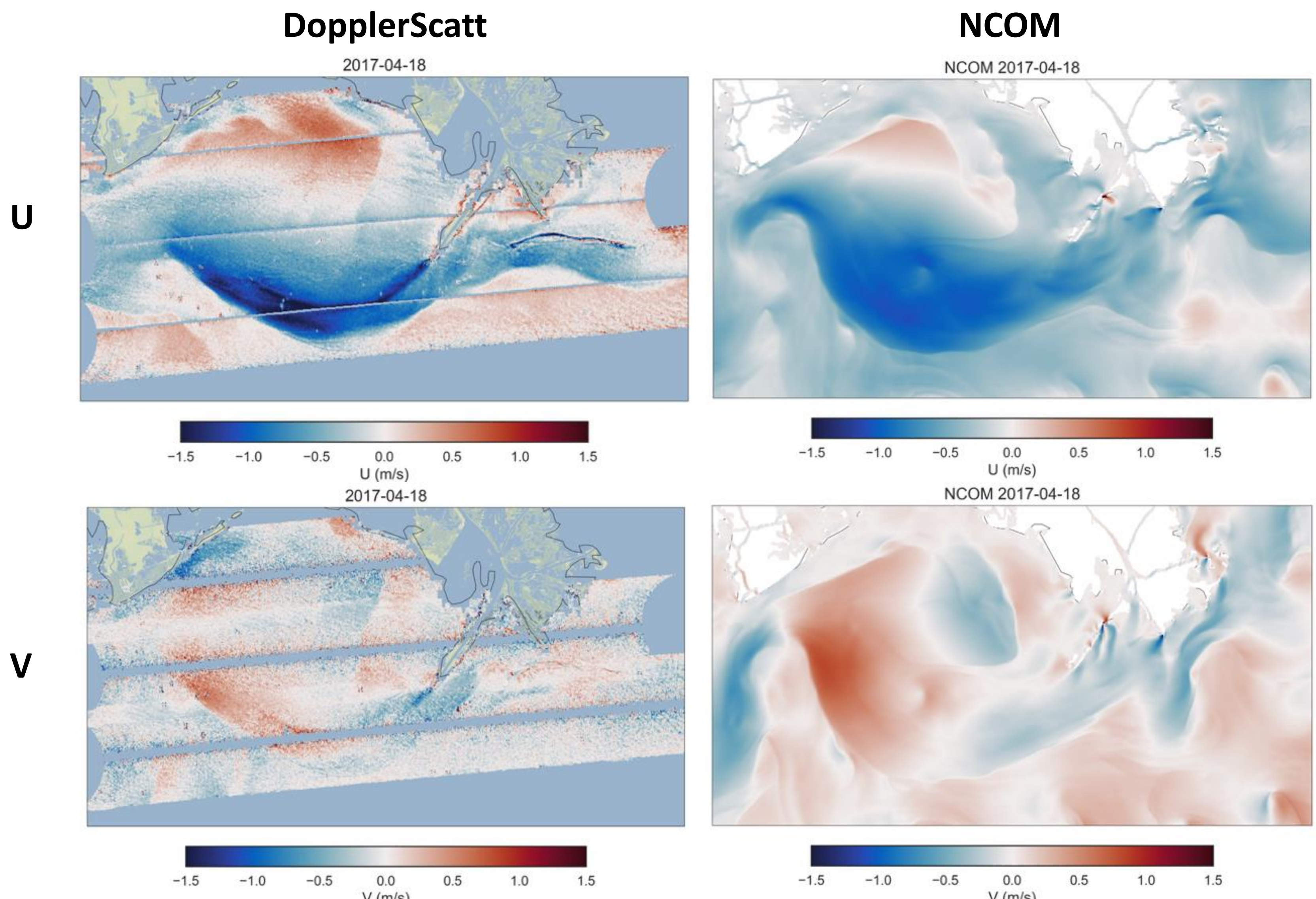
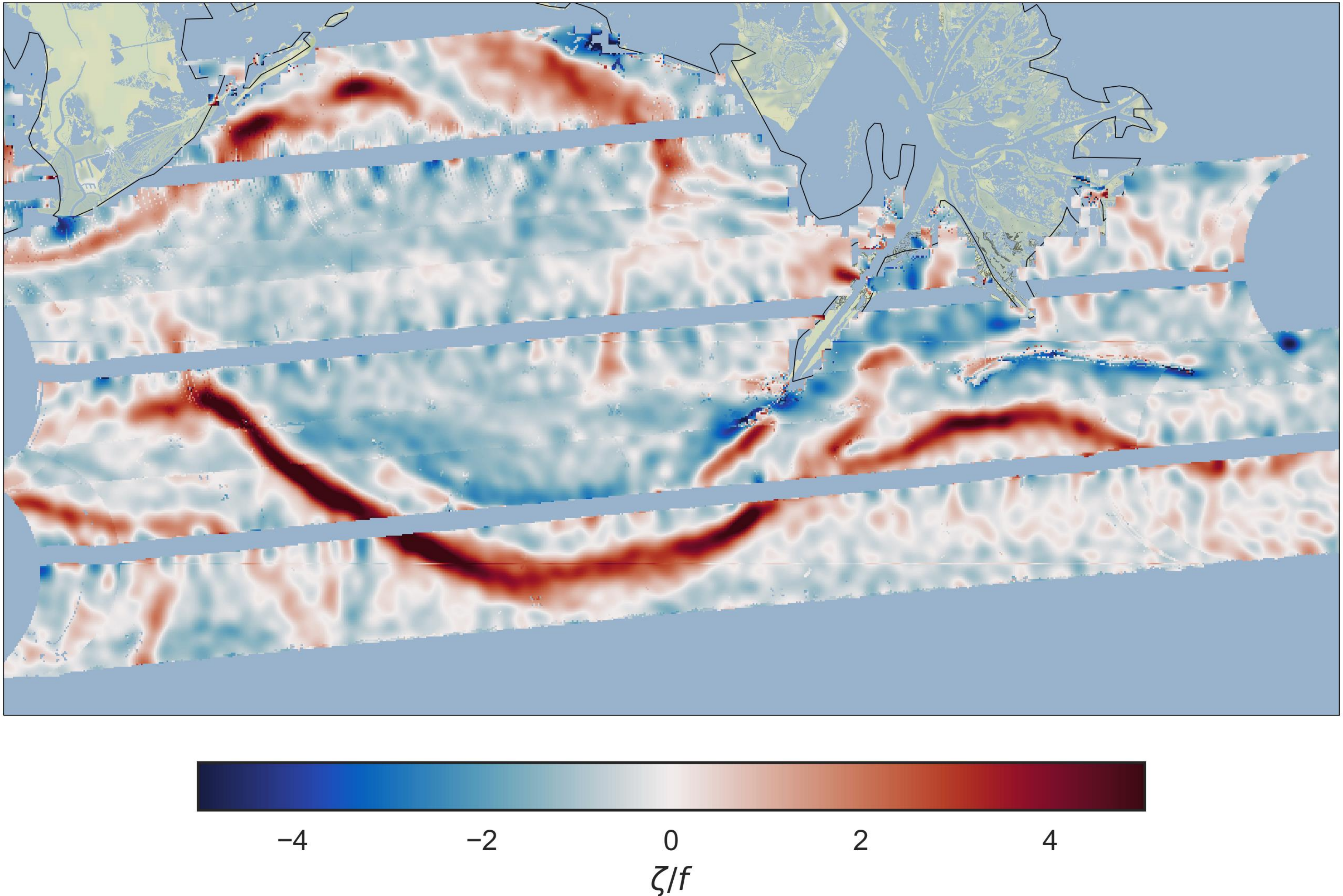
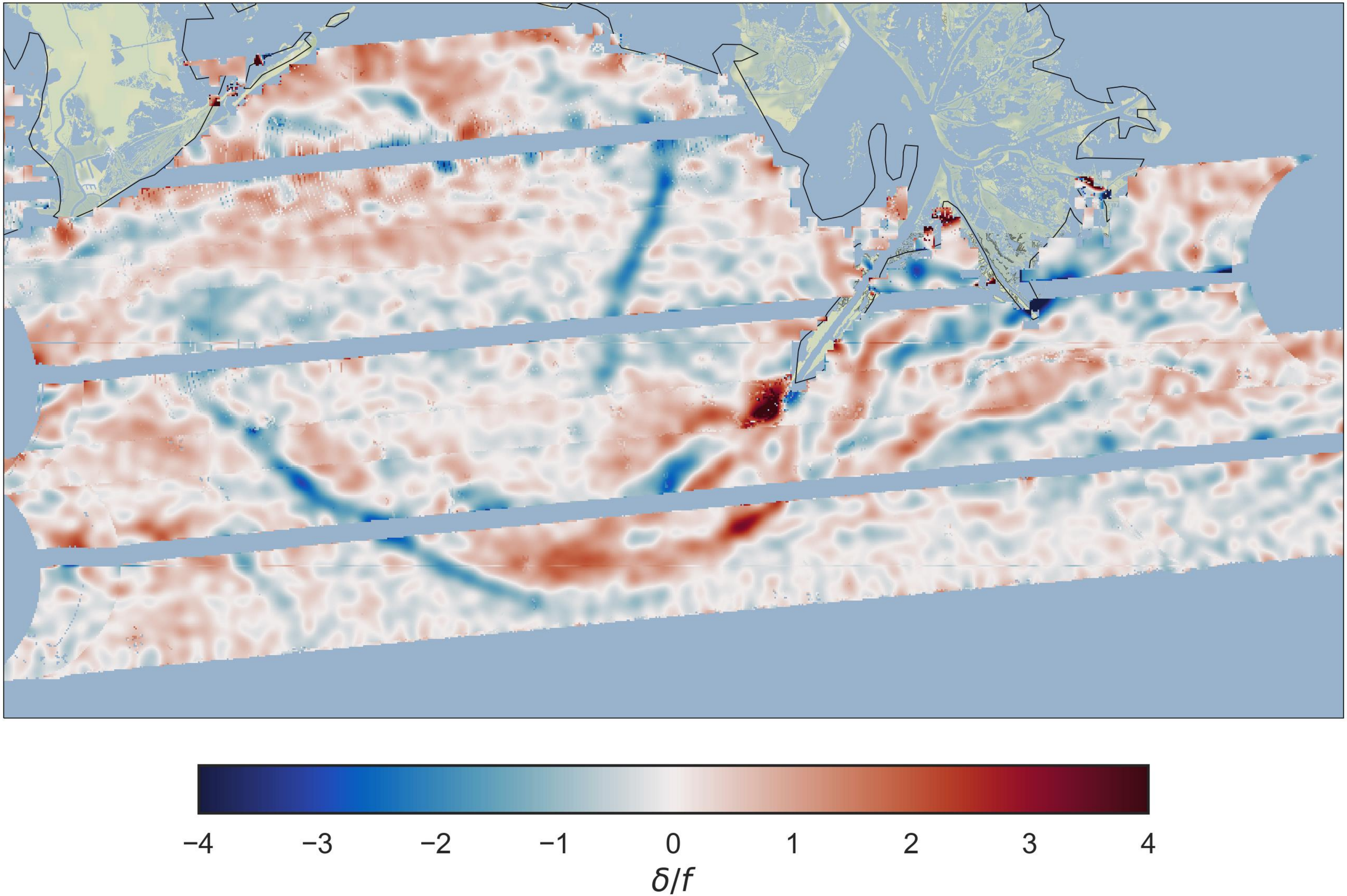
SPLASH 2017-04-18



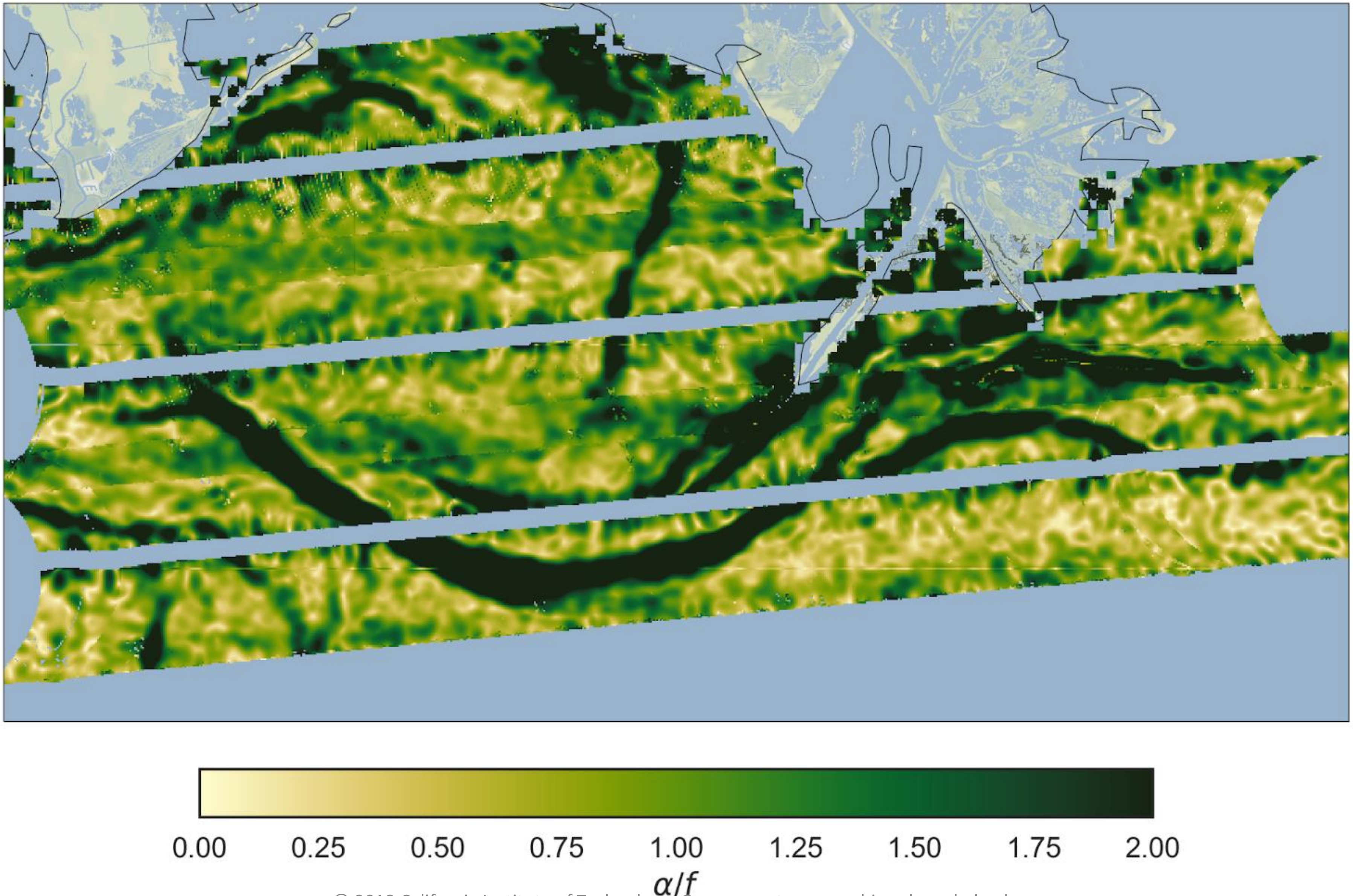
Vorticity



Divergence



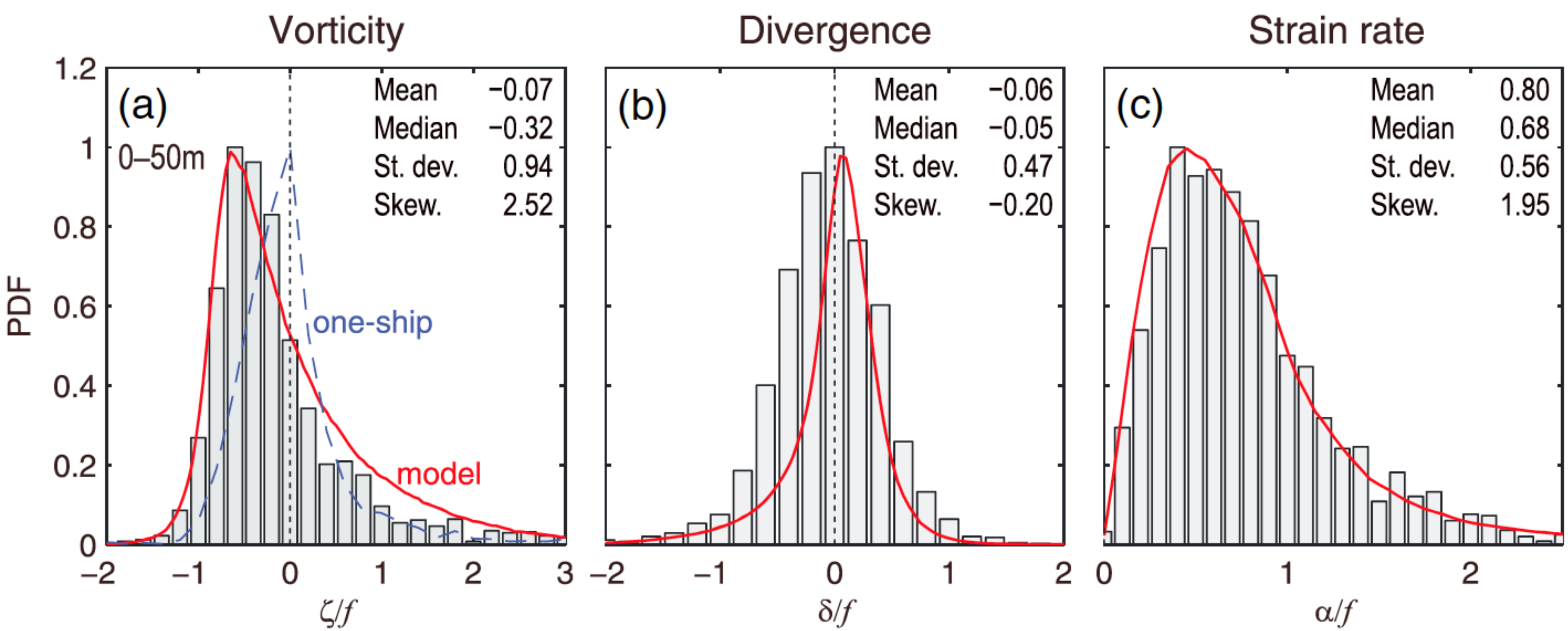
Strain Rate



Derivative PDFs
from Shcherbina et al., GRL, 2013

Data collected by two ships traveling 1 km apart in parallel for 500 km and using ADCPs

SHCHERBINA ET AL.: SUBMESOSCALE TURBULENCE STATISTICS



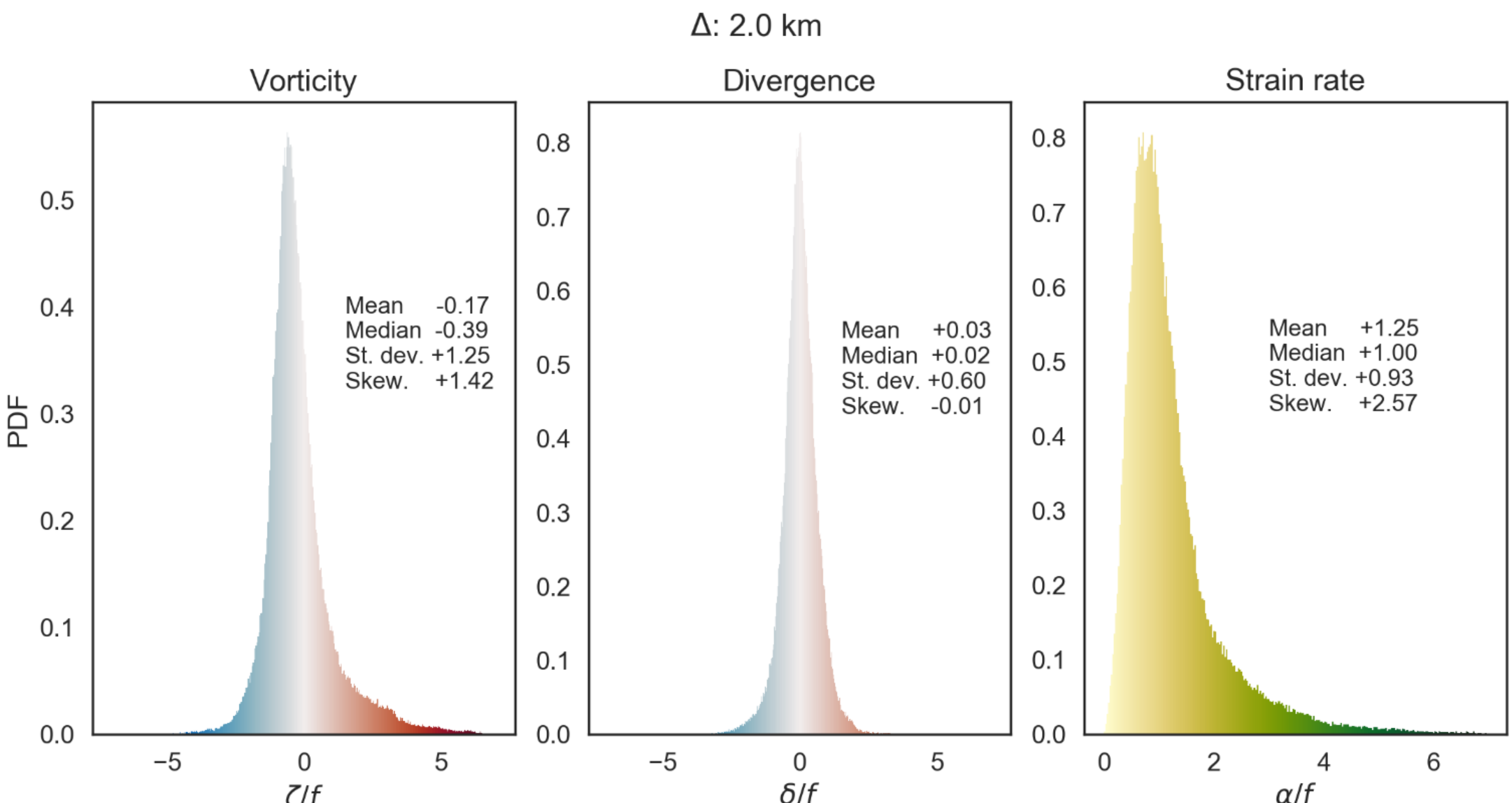
Skewness > 0 expected as ζ>0 structures have greater stability

Divergence range smaller than vorticity. Slightly skewed towards convergence.

Strain rate approximately chi-squared distributed.

DopplerScatt Derivative PDFs

Derivatives show similar statistics to Shcherbina et al. 2013



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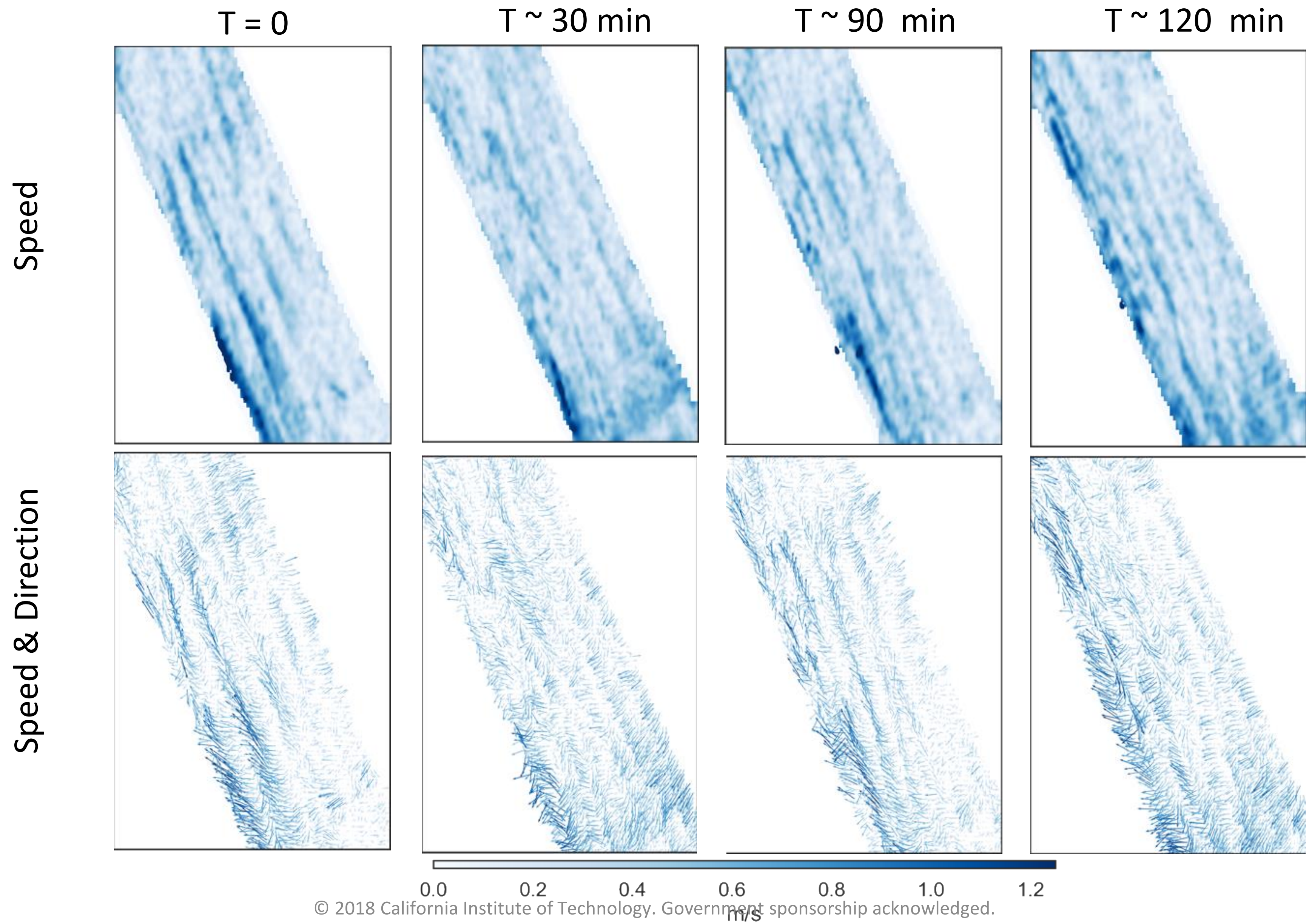
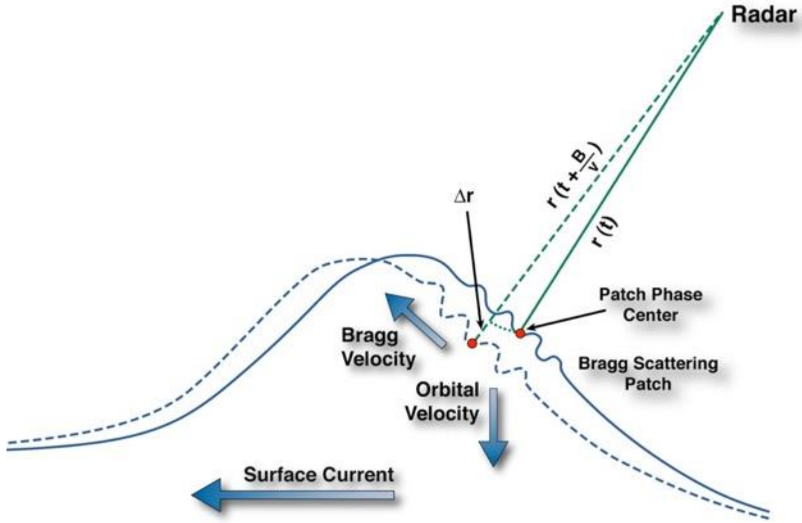
Fast Internal Wave Changes



What velocity are we measuring?

$$\Phi = \frac{2\pi}{\lambda}\Delta r$$

$$v_{scatterer} = \frac{\Delta r}{B} v_{platform}$$



- Radar sensitive to phase speed ~0.5 cm capillary waves (off-nadir) or tilts and small scale slope variations (near nadir)
- Free wave phase speed: ~31 cm/s. Capillary waves can also be generated as bound waves due to straining: will travel at straining wave phase speed (low wind speeds).
- Phase speed modulated by surface currents. Winds will add Stokes drift & surface drift.
- Gravity wave orbital velocity is added to capillary wave velocity. When averaging over surface waves, velocity is weighted (by radar brightness) spatial average.
- Brightness not homogeneous over long wave:
    - Hydrodynamic modulation due to 1) capillary amplitude modulation by spatially varying orbital velocity.; 2) wave breaking; 3) bound waves

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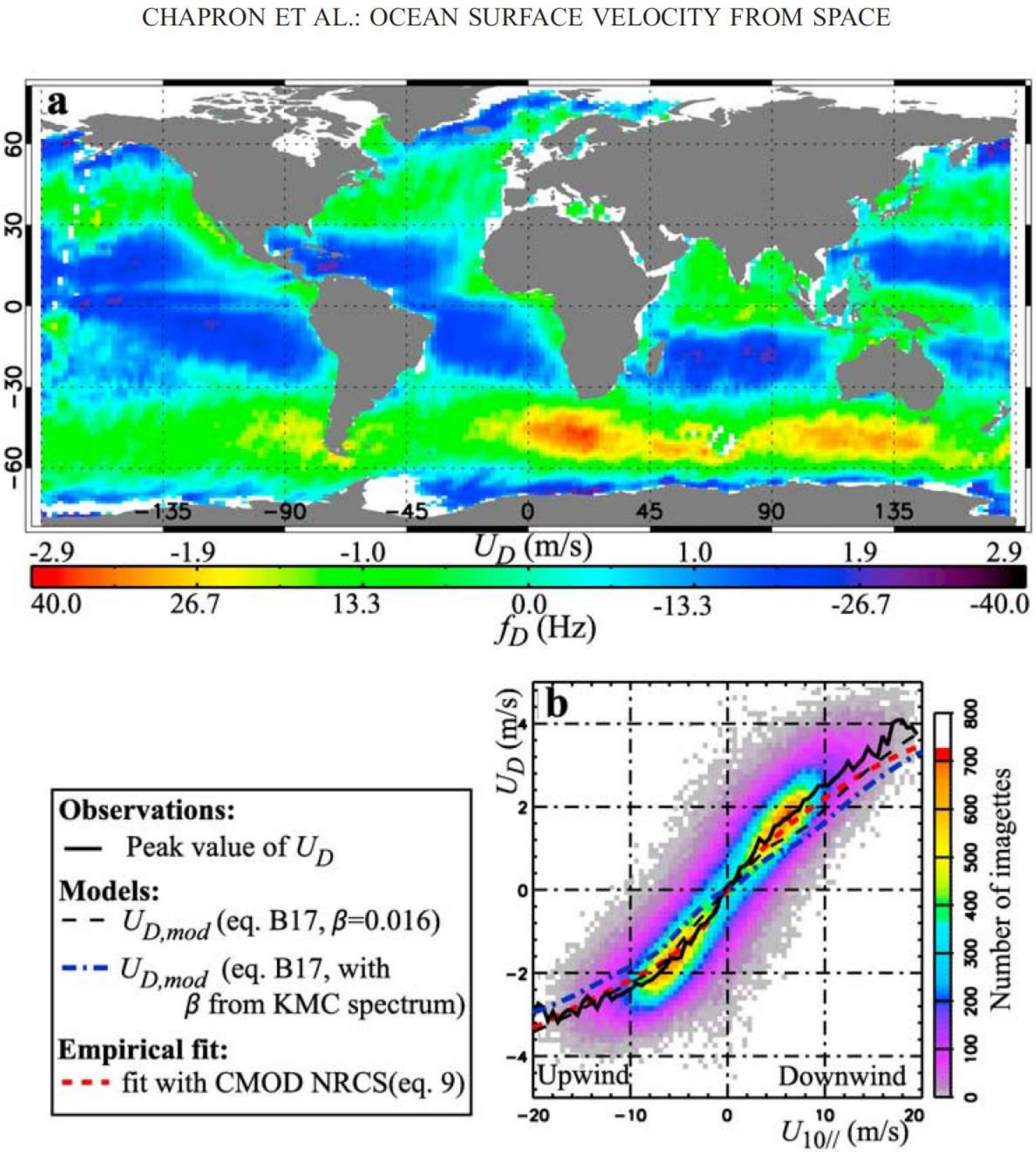
C-band Doppler Velocity Wind Dependence



Observation Model

$$\eta = \sum_n a_n \cos\Theta_n$$

Gravity wave height

In phase with *w*

$$\left.\frac{\delta\sigma_0}{\sigma_0}\right|_{\mathrm{Tilt}} = -m_T \cos\phi_r \sum_n a_n k_{xn} \sin\Theta_n = \frac{\partial \log\sigma_0}{\partial\theta} \cos\phi_r \eta_x$$

Tilt modulation

In phase with *u*

In phase with *w*

$$\left.\frac{\delta\sigma_0}{\sigma_0}\right|_{\mathrm{Hydro}} = m_r \sum_n a_n k_{xn} \cos\Theta_n - m_i \sum_n a_n k_{xn} \sin\Theta_n$$

Hydrodynamic modulation

Surface slope
Hilbert transform

Surface slope

$$\delta v_{rS} = \cos\phi_r \left(-\frac{\partial \log\sigma_0}{\partial\theta} \cot\theta \langle \eta_x w \rangle + \left\langle u \frac{\delta\sigma_0}{\sigma_0} \right\rangle \right) - \cot\theta \left\langle w \frac{\delta\sigma_0}{\sigma_0} \right\rangle$$

EM velocity bias

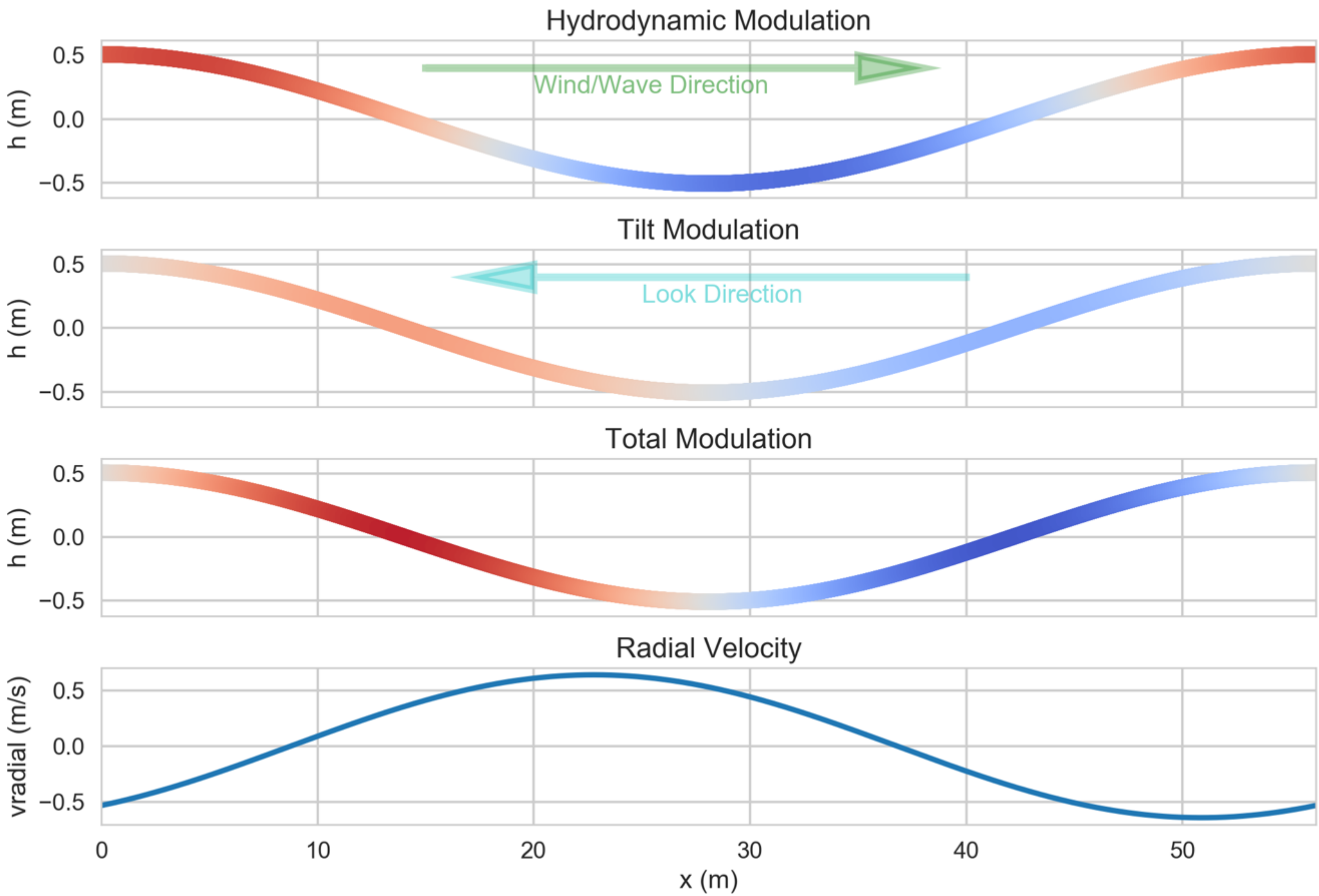
$$-\langle \eta_x w \rangle = U_S = \int dk\; k_x \omega F(k_x)$$

Stokes drift

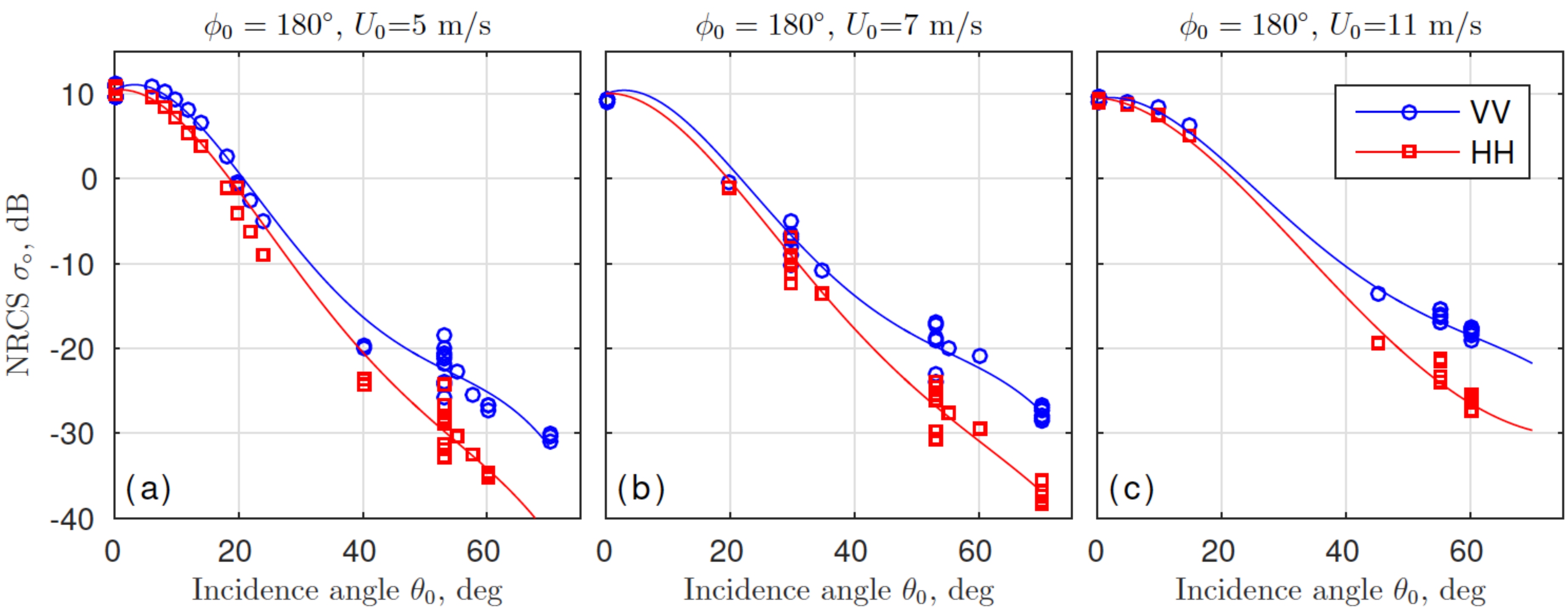
$$\delta v_S = U_S \left[\cos\phi_r m_r + \cot\theta \left(m_i + \cos\phi_r m_T \right) \right]$$

Net gravity wave contribution

Radar Brightness Modulation



Ka-Band Backscatter



Yurovsky et al. 2016

Tilt Modulation Near Nadir

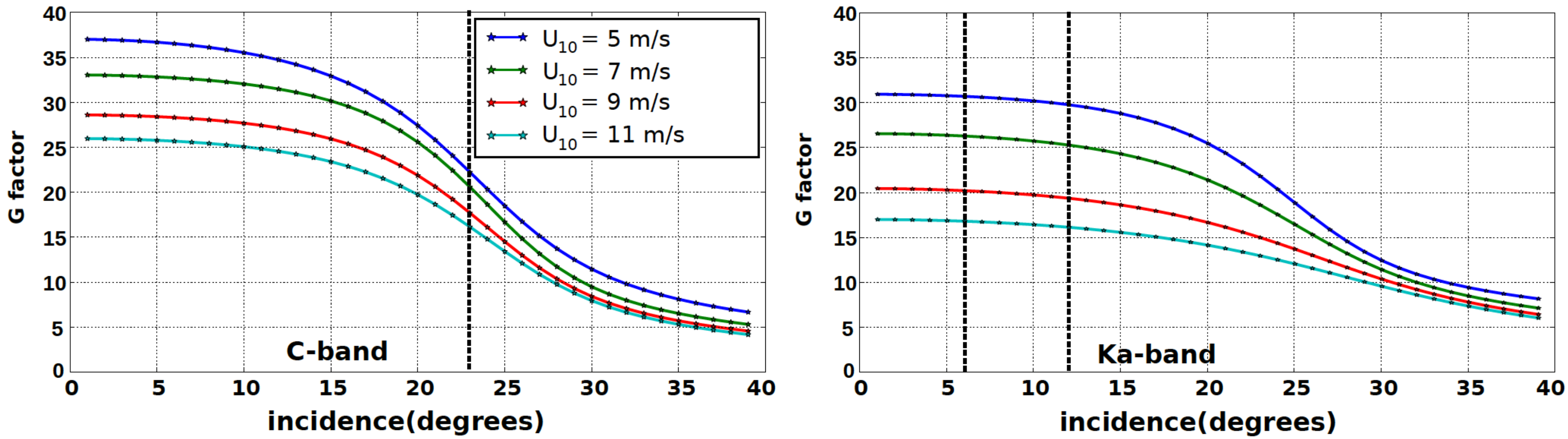
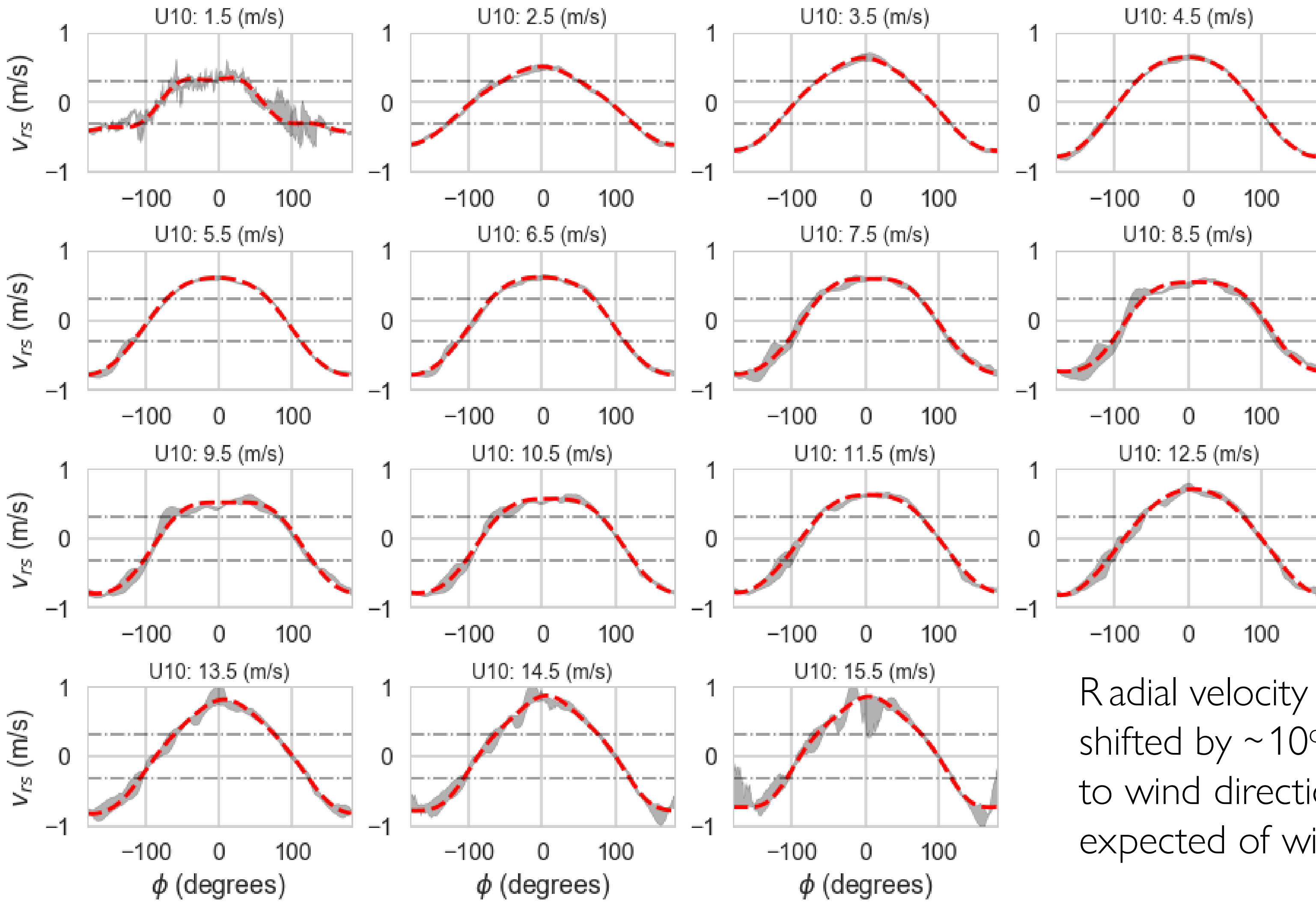


Figure 3. *G* factor estimated using a Kirchoff approximation, for a wave spectrum given by Elfouhaily et al. (1997), representing a fully developed sea state for wind speeds U_{10} ranging from 5 to 11 m/s. left: C band, appropriate for Envisat and Sentinel 1, right: Ka band for SKIM.

Ardhuin et al, 2018

Radial Velocities Binned by Wind Direction

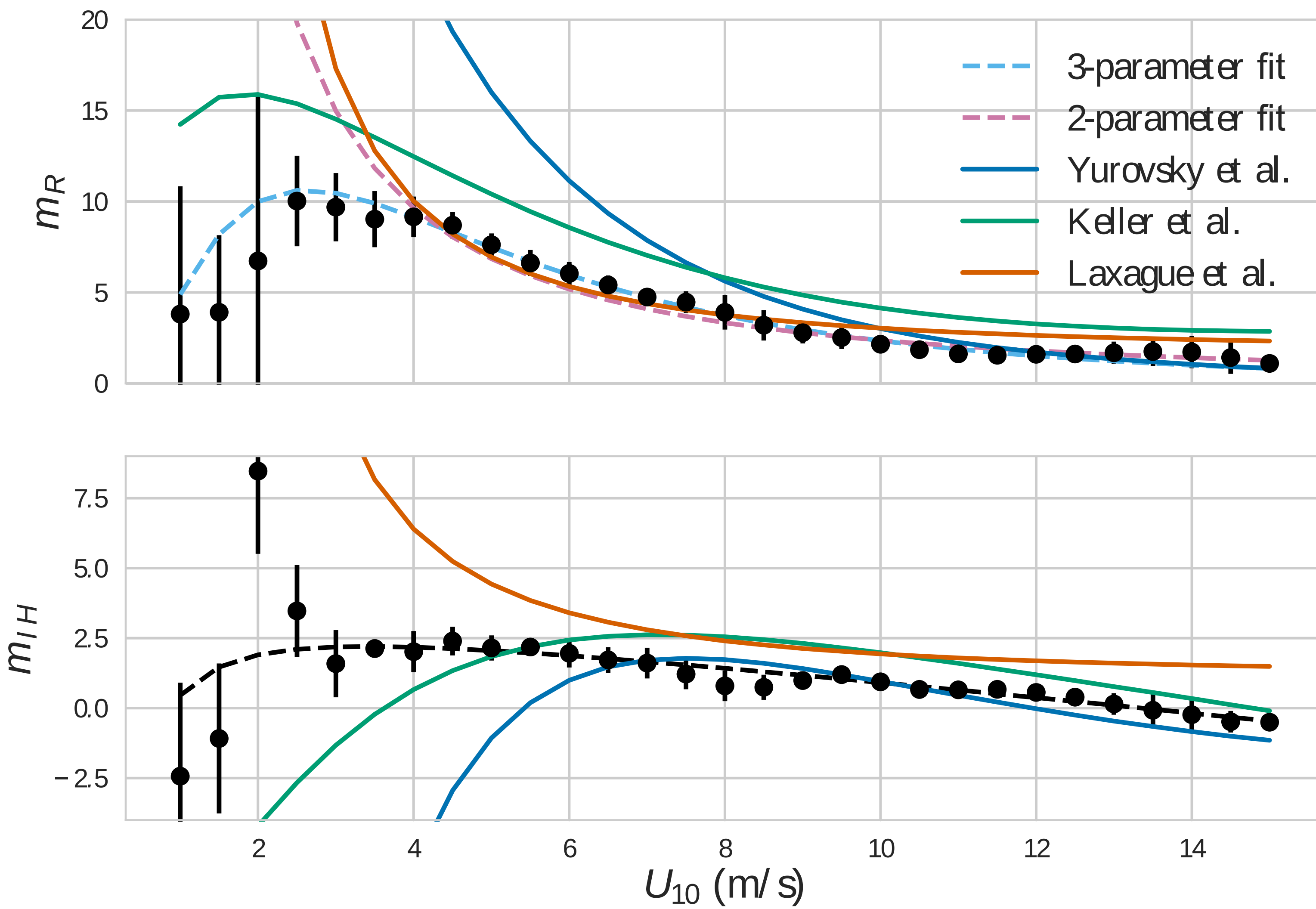
Dot-dash lines indicate Bragg phase velocities



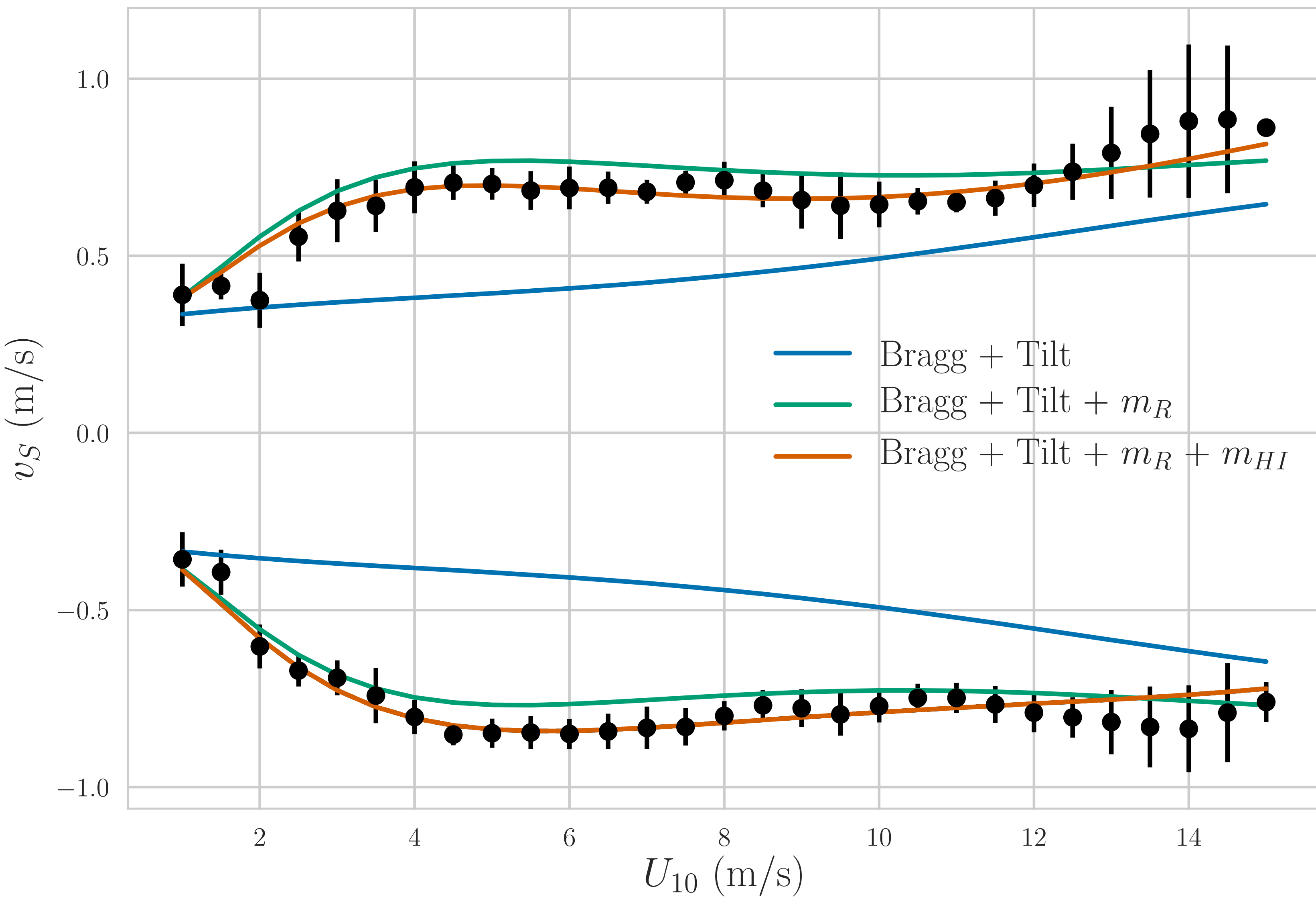
Radial velocity currents shifted by ~10° relative to wind direction, as expected of wind drift

This empirical averaging includes Stokes and surface drift contributions

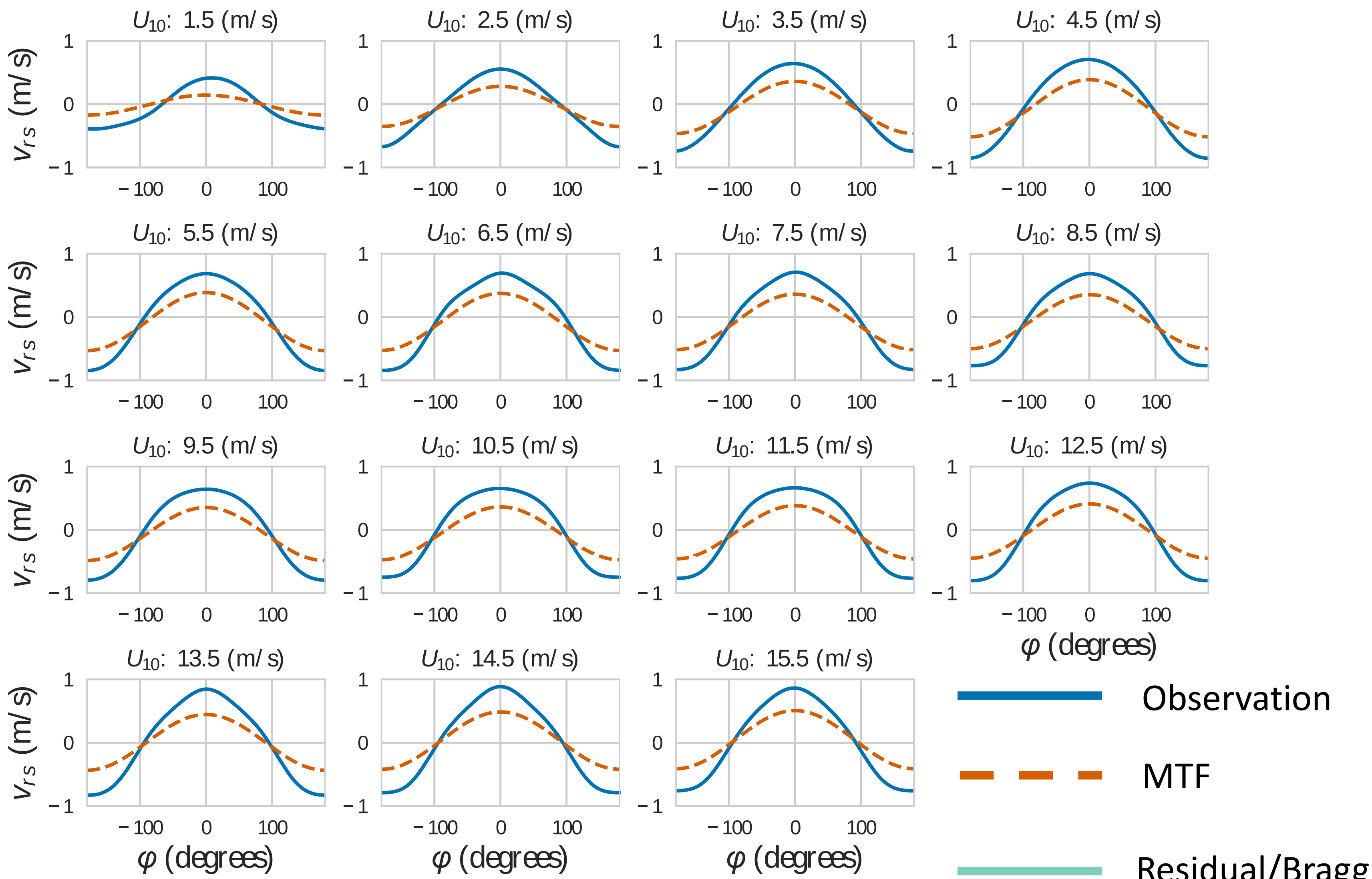
Hydrodynamic Modulation



Upwind/Downwind Velocities vs Theory

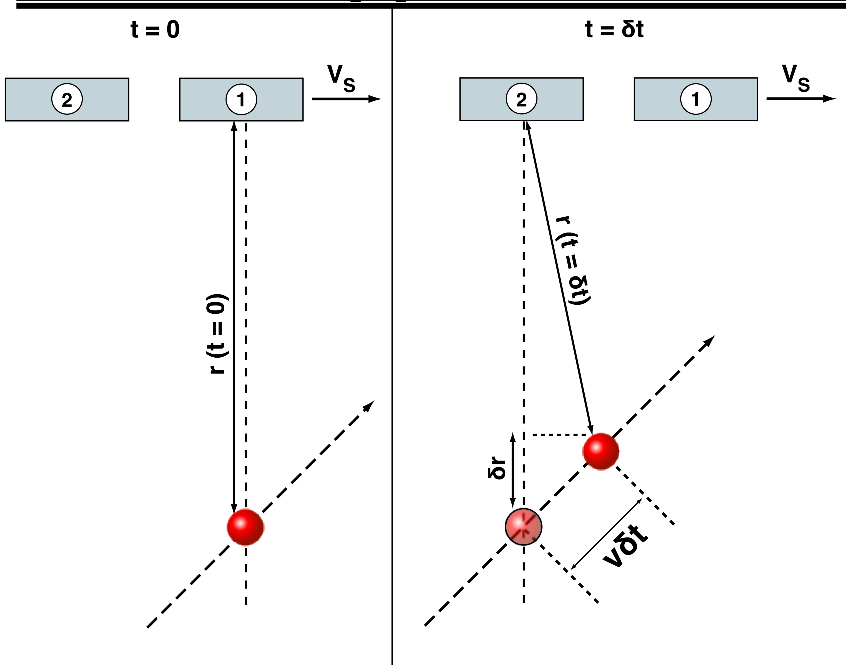


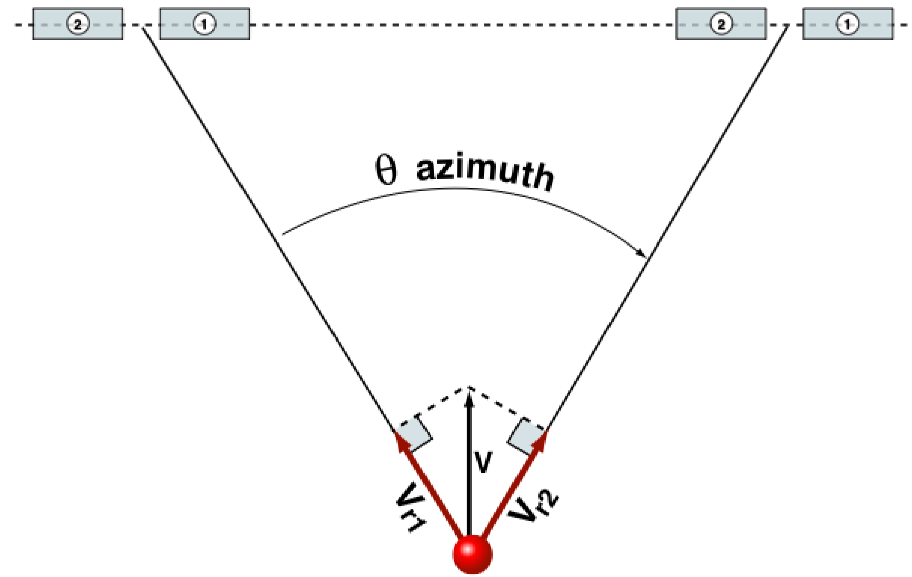
Radial Velocity Decomposition



BACKUPS

Doppler Current Measurement Concept





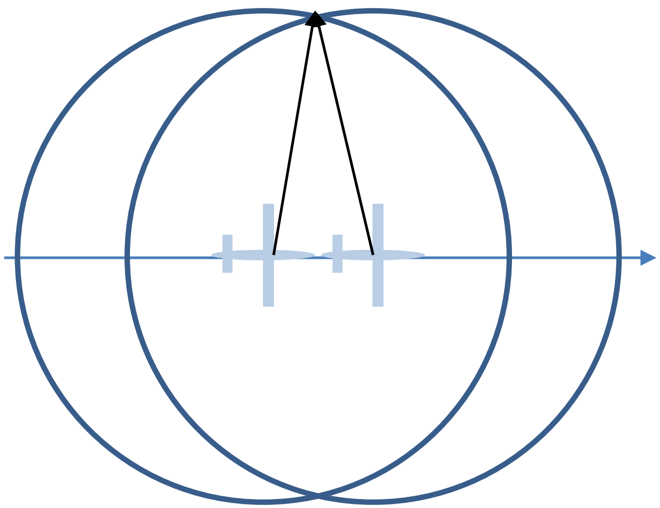
Vector currents are estimated by combining multiple (≧2) azimuth observations and projecting vector to the ocean surface.

Doppler Phase Difference: $\Delta\Phi = 2k\Delta r = f_D\delta t$

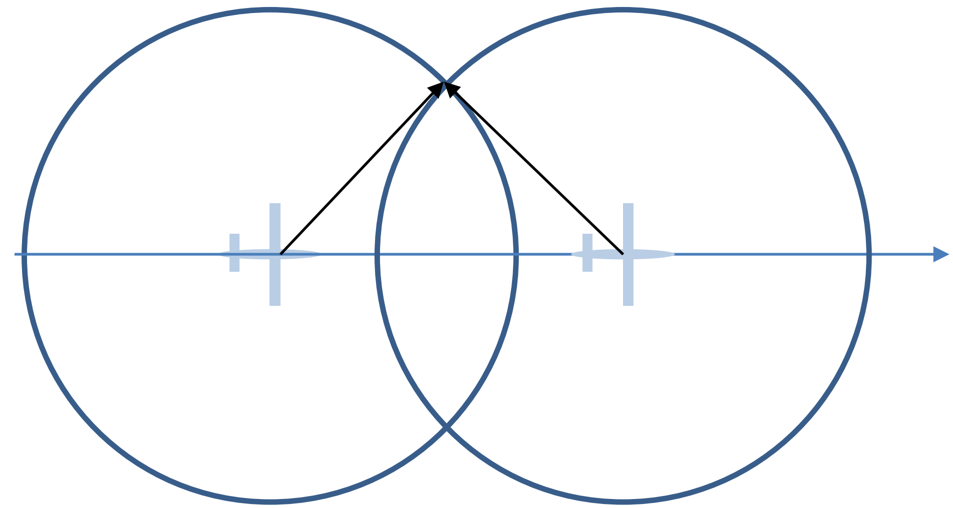
Radial velocity component: $v_r = \Delta r/\delta t = \Delta\Phi/(2k\delta t)$

- Radars provide coherent measurements: both the phase and the amplitude of a scattered signal are measured.
- The phase is proportional to the 2-way travel time (or range)
- The amplitude is proportional to the scattering strength of the traget
- Doppler measurements, f_D, are obtained by measuring the phase difference between pulses, $\Delta\Phi$. Noise is reduced by combining multiple pulses.

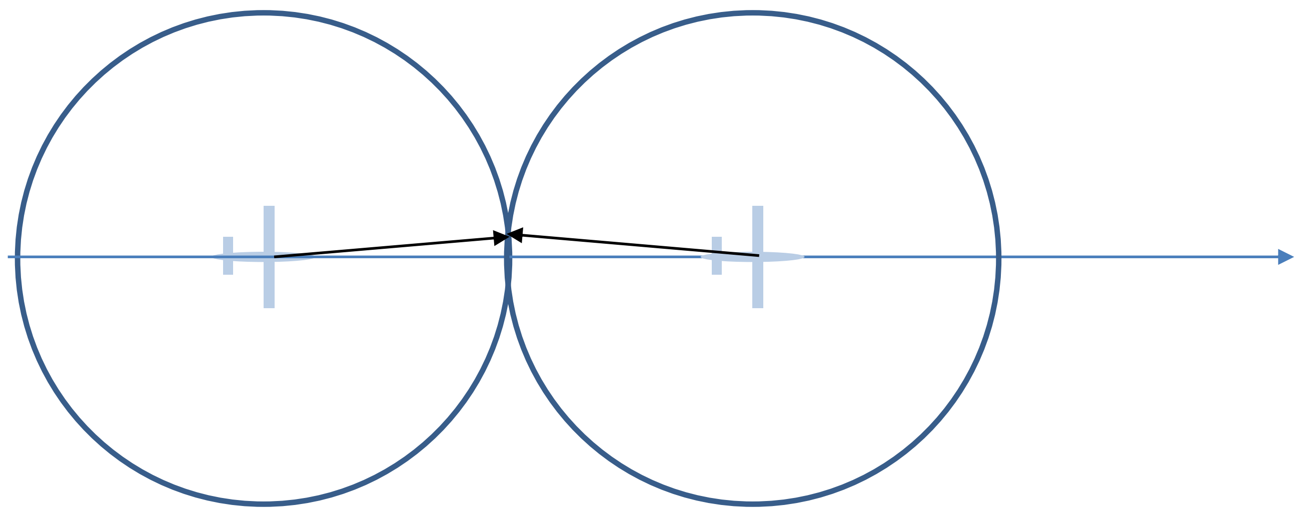
DopplerScatt Vector Estimation



Bad azimuth diversity

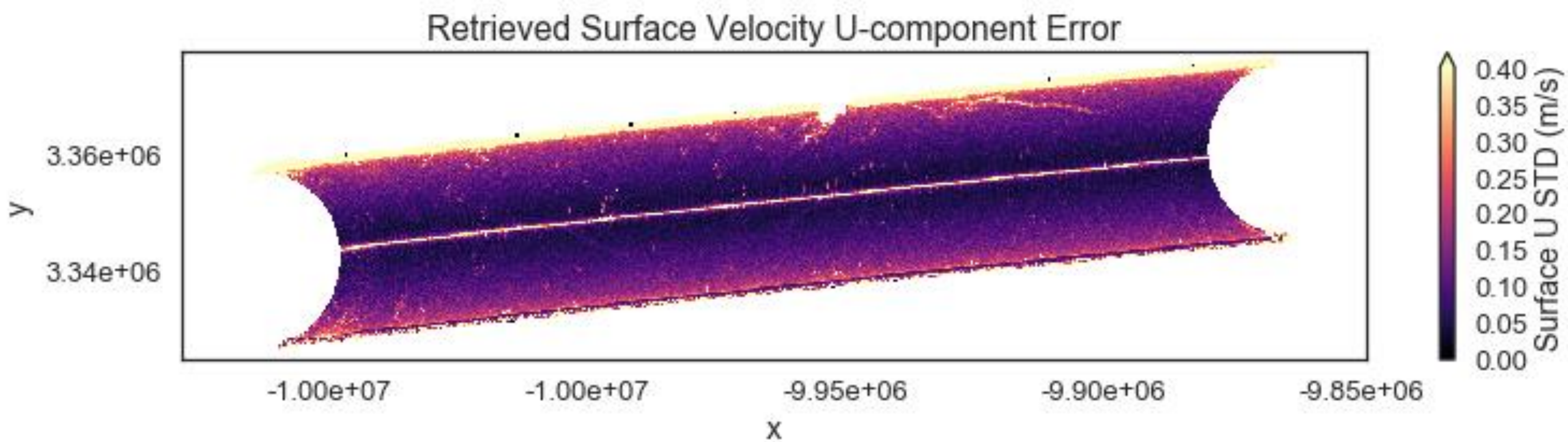


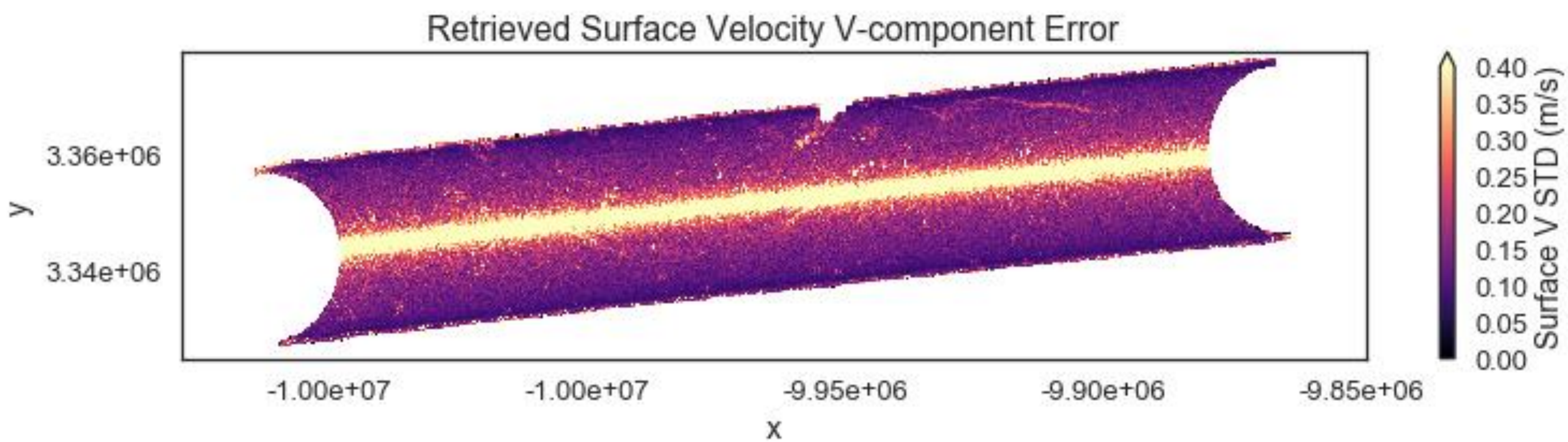
Good azimuth diversity



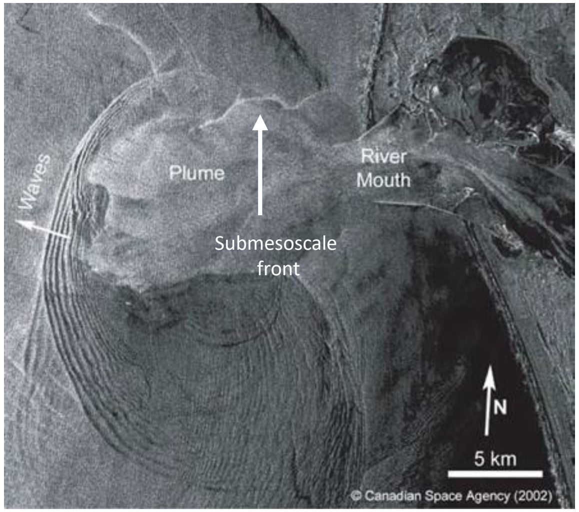
Bad azimuth diversity

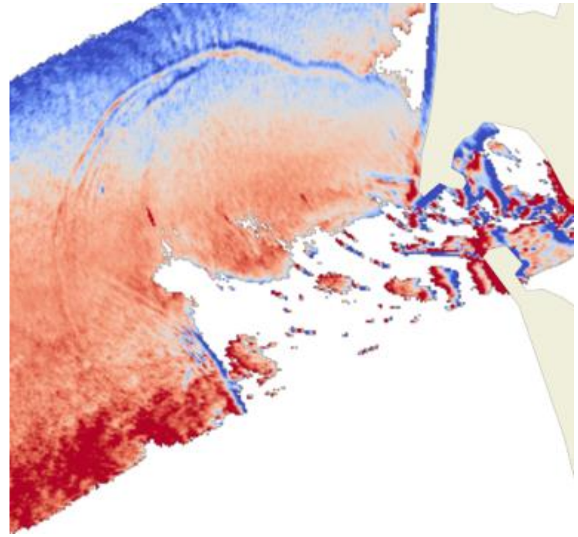
Retrieved Surface Velocity Errors

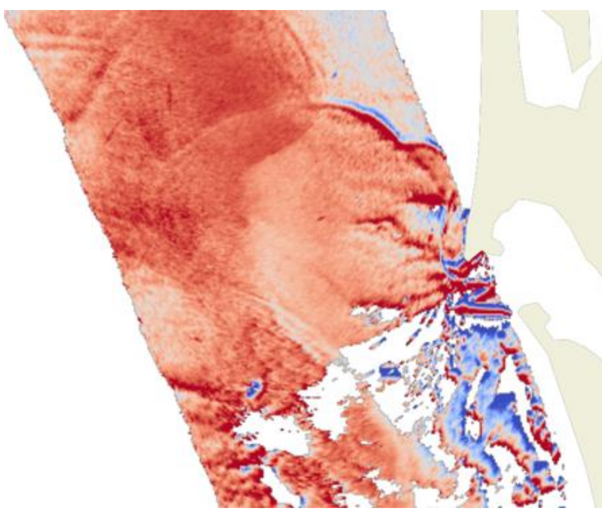


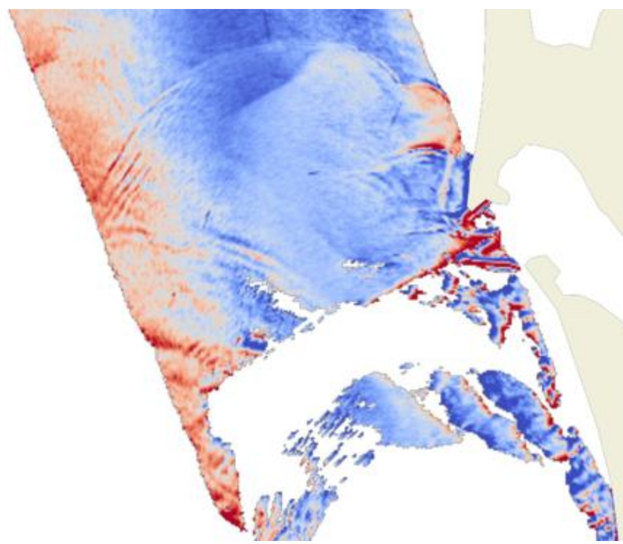


Columbia River Internal Wave Tidal Bore









Clockwise from top left:

1. Satellite SAR image of the Columbia river plume from Aug 9th 2002, Nash & Moum, Nature, 2005 showing internal waves generated by the plume. Another feature has been conjectured to be a submesoscale front (Akan et al, JGR submitted. J. McWilliams, personal communication)

2. DopplerScatt September 13th Track 1 fore-looking radial velocity

3. DopplerScatt September 13th Plume track fore-looking radial velocity

4. DopplerScatt September 13th Plume track aft-looking radial velocity